A three stage model for the inner engine of GRBs: Prompt emission and early afterglow

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We describe a model within the 'Quark-nova" scenario to interpret the recent observations of early X-ray afterglows of long Gamma-Ray Bursts (GRB) with the Swift satellite. This is a three-stage model within the context of a core-collapse supernova. STAGE 1 is an accreting (proto-) neutron star leading to a possible delay between the core collapse and the GRB. STAGE 2 is accretion onto a quark-star, launching an ultrarelativistic jet generating the prompt GRB. This jet also creates the afterglow as the jet interacts with the surrounding medium creating an external shock. Slower shells ejected from the quark star (during accretion), can re-energize the external shock leading to a flatter segment in the X-ray afterglow. STAGE 3, which occurs only if the quark-star collapses to form a black-hole, consists of an accreting black-hole. The jet launched in this accretion process interacts with the preceding quark star jet, and could generate the flaring activity frequently seen in early X-ray afterglows. Alternatively, a STAGE 2b can occur in our model if the quark star does not collapse to a black hole. The quark star in this case can then spin down due to magnetic braking, and the spin down energy may lead to flattening in the X-ray afterglow as well. This model seems to account for both the energies and the timescales of GRBs, in addition to the newly discovered early X-ray afterglow features.

Keywords: Gamma ray bursts

1. Introduction

Prior to the launch of Swift, the gamma ray burst (GRB) afterglow was thought to follow a power-law (or possibly two power laws, where the break is due to the jet break [1]). However, Swift showed that the X-ray afterglow light curve starting from about 100 seconds after the GRB trigger in many cases cannot be described by a power law. Instead, it can be divided into several phases, as shown in Fig. 1. Not all stages are present in all bursts. The first stage is a very sharp drop off, thought to be due to the curvature effect [2]. Thereafter a flatter segment lasting for 10^4 to 10^5 seconds is often seen [3], followed by the two power laws mentioned earlier (denoted "Late/Classical afterglow" in Fig. 1). In some cases this flat segment is followed by a very sharp drop off, before the classical afterglow starts. Overlaid on the initial sharp drop off and on the flat segment can be one or more flares.

The flaring activity and flat segments followed by a sharp drop off in the X-ray afterglow is a very strong indication that the engine is still powering the light curve [4]. Therefore the inner engine must not only be able to explain the energetics and duration of the prompt gamma ray emission, but also long lasting features in the afterglow.
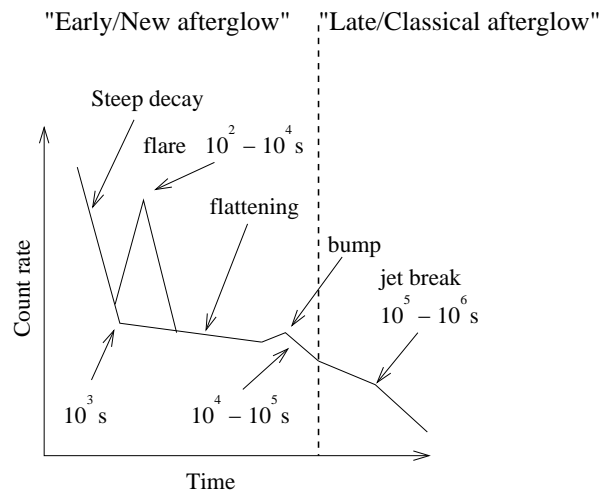

Fig. 1. Generic X-ray afterglow (e.g. [5]). A steep decay often follows the prompt emission. Then a flat segment is commonly seen, before the afterglow decays following one or two power laws. The flat segment can also be followed by a steep decay (not shown), indicating that the flat segment was caused by inner engine activity. Such flat segment with steep decay is the topic of this paper. Overlaid on the initial steep decay and the flat segment is sometimes one or more flares.

In this paper we discuss how a quark star (QS) as the engine can explain these observed features. In our model, the prompt emission is caused by internal shocks [6] in an ultrarelativistic jet, launched by accretion onto a QS. Flares are also caused by internal

shocks, either by continued accretion onto the QS, or if the QS collapsed to a black hole (BH), by accretion onto a BH. A flat segment not followed by a sharp drop off can be explained by refreshed shocks [7], i.e. slower shells emitted during the prompt phase slowly catching up with the external shock refreshing it, or by extended engine activity. A sudden cessation in the extended engine activity can explain a flat segment followed by a sharp drop off in the observed light curve. Extraction of the QS spin energy can explain such a long lasting engine activity. If the QS collapses to a BH during spin down, the engine activity will end suddenly and a sharp drop off can be seen.

We will describe the model in section 2, and in particular discuss how a flat segment followed by a sharp drop off sets an upper limit on the magnetic field, if one assumes that the flat segment is due to extraction of spin energy. On the other hand, the quark star magnetic field must be strong enough to channel the accreting material to the polar cap, something that puts a lower bound on the magnetic field. In section 3 we will take GRB 070110 as an example (a burst that show a flat segment followed by a sharp drop off), and use the theory from section 2 to show that we can consistently account for both the energetics and duration of the prompt phase and the plateau phase. We summarize in section 4.
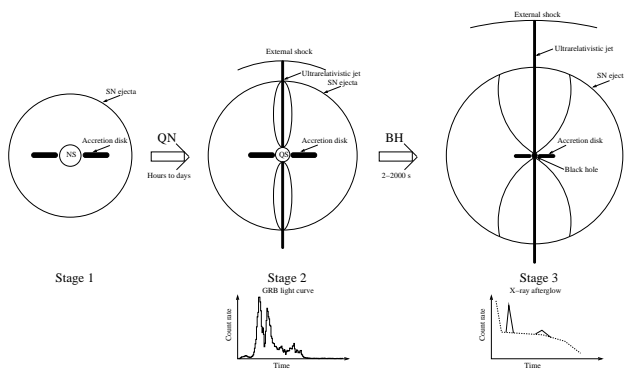
2. Three stages model

Fig. 2.   The three stages model for a GRB inner engine. *Stage 1:* A neutron star is formed in the core collapse of a massive star. *Stage 2:* An ultrarelativistic jet launched from hyperaccretion onto a QS generates the GRB. *Stage 3:* An ultrarelativistic jet from a BH collides with slower parts of the QS jet and creates flaring.

2.1. *Stage 1*

In [8], a three stage model for long GRBs was proposed (see Fig. 2). Stage 1 is a (proto-) neutron star phase, the neutron star being born in the collapse of the iron core in an initially massive star. This neutron star can be transformed to a QS, either through spin-down [9] or through accretion, thereby increasing its central density sufficiently that it can form strange quark matter. This stage could lead to a delay between the core collapse and the GRB. The collapse into a QS, in a quark nova [10] (QN), releases up to 10^{53} ergs that might help power the explosion of the star. This can possibly explain why GRB associated supernovae are often very energetic [11, 12], and depending on the size of the stellar envelope this might also create a GRB precursor [12]. If a QS is formed directly in the core collapse, stage 1 will be bypassed and the process starts from stage 2. The same amount of energy will still be emitted from the conversion to a QS, allowing these features even if stage 1 is bypassed.

2.2. *Stage 2*

Stage 2 is the QS stage. Accretion onto the QS surrounded by a hyperaccreting debris disk from the collapse launches a highly variable ultra-relativistic jet, in which internal shocks can give rise to the gamma radiation seen in a GRB [13]. In order for a jet to form, the accreting material has to be channeled to the polar cap. This sets a lower limit on the QS magnetic field, in that the Alfvén radius has to be at least twice the radius of the star. The Alfvén radius is given by:

$$r_{\rm A} = \left(\frac{B^2 R_{\rm QS}^6}{\dot{m}\sqrt{2GM_{\rm QS}}} \right)^{2/7}. \qquad (1)$$

In this equation G is the gravitational constant, $M_{\rm QS}$ is the QS mass, $R_{\rm QS}$ is the QS radius, $\dot{m}$ is the accretion rate which is constrained by observed energetics of the burst, and B is the QS magnetic field. Later we will find the maximum magnetic field in order to explain the flat segment in GRB 070110, and we can use this together with the Alfvén radius to find an estimate for $\dot{m}$, and compare this to what is required to explain the prompt emission.

If the QS survives the accretion phase and is rapidly rotating, a stage 2b can be reached in which magnetic braking spins the star down extracting

about 10^{52} ergs in rotational energy. Magnetospheric currents escapes through the light cylinder, thereby launching a secondary outflow and spinning down the QS, whose magnetic field is aligned with the rotation axis. The spin down luminosity [14] is given by:

$$L \sim 4 \times 10^{48} \text{ erg s}^{-1} \left(\frac{B_0}{10^{15} \text{ G}} \right)^2 \left(\frac{2 \text{ ms}}{P_0} \right)^4 \left(1 + \frac{t}{\tau} \right)^{-5/3} \tag{2}$$

where the characteristic spin-down time (in seconds) is,

$$\tau = 3.5 \times 10^3 \text{ s} \left(\frac{10^{15} \text{G}}{B_0} \right)^2 \left(\frac{P_0}{2\text{ms}} \right)^2 \left(\frac{M_{\text{QS}}}{1.4 M_\odot} \right) \left(\frac{10\text{km}}{R_{\text{QS}}} \right)^4 \tag{3}$$

In the above equations t is time since the beginning of spin down, P_0 is the initial spin period, and B_0 is the initial magnetic field strength.

There will be a break in the spin down luminosity at $t = \tau$. After the break the spin-down luminosity will follow a power law with power $-5/3$, however, this might not be the observed light curve power. If, on the other hand, this secondary outflow created by spinning down the QS ends abruptly, a much sharper drop off will be seen, as the light curve drops down to the level given by the external shock. This can occur if the quark star collapses to a BH during spin down. Unless a disk exists around the BH, the rotational energy of the BH cannot be extracted and the engine has been shut off.

2.3. *Stage 3*

If the QS (in the process of ejecting the shells) accreted a sufficient amount of matter, it can collapse into a BH, which leads to stage 3. Stage 3 is accretion onto the BH which launches another ultra-relativistic jet [15]. Interaction between this jet and the jet from the QS can give rise to flaring commonly seen in the X-ray afterglow of GRBs. Internal shocks within the BH jet itself can also lead to flaring activity. Alternatively, if the QS did not collapse to a BH, continued accretion onto the QS after the prompt phase might also explain X-ray flaring. The BH jet might be very powerful, so if it catches up with the external shock a bump might be seen in the light curve. The relevant features and emission have been discussed in details in [8].

3. Application of our model to GRB 070110

Based on the observed duration of the flat segment in a burst, we use Eq. 3 to find the magnetic field required to spin the star down in this time (assuming that the star collapsed to a BH at $t = \tau$). This will give an upper limit to the magnetic field, since if the magnetic field is weaker, τ is larger than the time of collapse. Having an estimate for the magnetic field, we can go on to estimate the spin down luminosity using Eq. 2. This spin down luminosity can be compared to the observed luminosity. We assume that 10% of the spin down luminosity can be converted into X-ray photons. Furthermore, in order to explain the prompt emission, we can estimate the accretion rate that this magnetic field can channel to the polar cap. Since the estimate of the magnetic field gave a maximum, this leads to a maximum possible accretion rate. We now apply this method to GRB 070110, a burst that show a very sharp drop off following a flat segment (see Fig. 3).
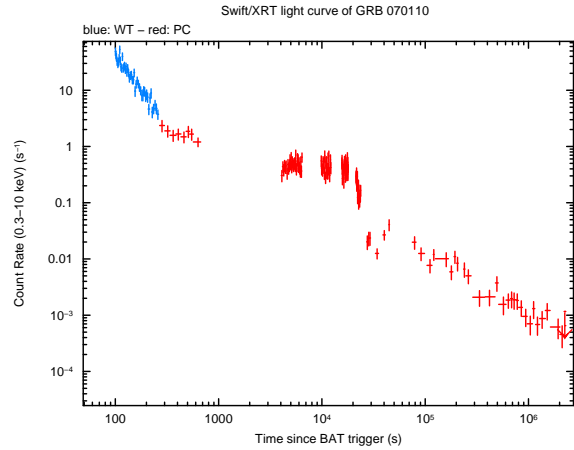

Fig. 3.   The X-ray afterglow light curve of GRB 070110 [16]. A flat segment is clearly seen lasting up to about 20000 seconds (about 6000 seconds when corrected for cosmological time dilation), followed by a very sharp decay. The flat segment we explain as being due to extraction of spin energy from a rapidly rotating QS. The QS collapsed to a BH, ending the secondary outflow created by the spin down and leading to the sharp drop off in the light curve, as the light curve drops down to the level given by the external shock.

The maximum magnetic field found by setting $t = \tau$ is 6.8×10^{14} G. The corresponding maximum spin down luminosity is 1.6×10^{48}erg/s. The observed luminosity during the flat segment is $L_{\text{Obs,iso}} \approx 10^{48}$erg/s [4]. If we assume a 10 degree opening an-

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gle for this outflow, this corresponds to $L_{\mathrm{Obs},10} \approx 1.5 \times 10^{46}$erg/s. Even when we assume that 10% of the spin down luminosity goes into radiation, we see that we have 10 times more energy than required to explain this burst.

A magnetic field of 6.8×10^{14} G can channel $7.5 \times 10^{-4} M_{\odot}$/s (Eq. 1) to the polar cap. If we assume that 1% of the total gravitational energy of the accreted material is converted to prompt radiation, this corresponds to 3.8×10^{50} erg in prompt gamma radiation. Assuming that the beaming angle of this GRB was 10 degrees, the observed gamma ray energy in this burst was $E_{\gamma} \sim 1 \times 10^{50}$ erg. Again, we get more energy than required in order to explain this burst. The reason for this can be that we have overestimated the magnetic field, i.e. the QS collapsed at $t_{\mathrm{collapse}} < \tau$, that we have overestimated the efficiency with which gamma radiation is produced, that the majority of the energy is radiated at frequencies not observed by SWIFT, or that the beaming angle is larger.

4. Summary

The properties of the three stages (initiated by the collapse of the iron core in an initially massive star) of the inner engine in our model are:

- If a neutron star is left behind, it can collapse to a quark-star at a later stage, creating a delay between the supernova and the GRB.
- Accretion onto the quark-star generates the GRB by powering an ultrarelativistic jet. Internal shocks in this jet create the GRB.
- Accretion continues, but at some point it cannot heat up the star sufficiently. This halts the emission of shells, ending the GRB.
- If the quark-star accretes a sufficient amount of matter, it collapses into a black-hole. Further accretion onto the black-hole launches an ultrarelativistic jet.
- If the QS does not collapse to a black-hole and is rapidly rotating, magnetic braking of the QS can extract the rotational energy. This process can last for $10^4 - 10^5$ seconds. About 10^{52} ergs can be extracted this way.

The emission features in our model can be summarized as follows:

- Early, steep decay in the X-ray afterglow is due to the curvature effect.
- Flares are created by interaction between the jet from the accretion onto a black-hole and slower parts from the jet from the quark-star.
- Re-energization of the external shock (seen as flattening of the X-ray afterglow light curve) is due only to the jet from the quark-star. Slower parts of this jet re-energizes the external shock.
- If spin-down energy from the QS is extracted, this outflow (mainly in the form of e^+e^- pairs) can scatter photons from the external shock creating a flat segment in the X-ray afterglow, see [17].
- If a black-hole is formed the jet from the black-hole can collide with the external shock from the GRB, creating a bump in the afterglow light curve.

In conclusion, we have presented a three stage model for the inner engine for GRBs. This model seems to be able to account for the observed prompt gamma ray emission, as well as the features of the early X-ray afterglow.

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